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The uniformity illusion: Central stimuli can determine peripheral perception

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Vision in the fovea, the centre of the visual field, is much more accurate and detailed than in the periphery. This is not in line with our rich phenomenology of peripheral vision. Here, we present a visual illusion that shows that detailed peripheral visual experience is partially based on a reconstruction of reality. Observers fixated on the centre of a visual display where central stimuli differ from peripheral stimuli. Over time, central stimuli appear in the periphery such that the display seems uniform. We show that a wide range of visual features are susceptible to a uniformity illusion, including shape, orientation, motion, luminance, pattern and identity. We argue that the uniformity illusion is the result of a reconstruction of sparse visual information (from the periphery) based on more readily available detailed visual information (from the fovea) giving rise to a rich, but illusory, experience of peripheral vision.

Vision in the fovea, the centre of the visual field, is accurate and detailed. In the periphery, however, visual resolution and colour sensitivity are limited (Anderson, Mullen, & Hess, 1991; Westheimer, 1982). Retinal output to the cortex for stimuli in the periphery has limited spatial resolution and colour information. This makes it more difficult to identify pictures (Thorpe, Gegenfurtner, Fabre-Thorpe, & Bulthoff, 2001) or read words (Rayner & Bertera, 1979) presented in the periphery. Introspectively vision seems rich and detailed for most of the visual field (Block, 2007; Block, 2011; Lamme, 2006; Rahnev et al., 2011). How can this seemingly rich visual experience result from limited retinal output? Perhaps our actual experience is rich and detailed because the brain supplements the details and richness when bottom-up input is poor.

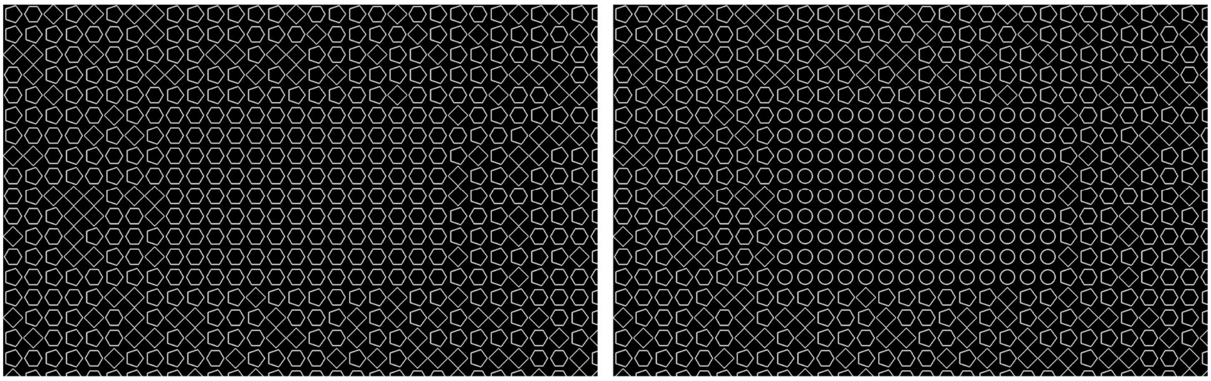


Fig 1:
Two examples of a display that can evoke a uniformity illusion. To experience the illusion, view panel A or B from close range so that the display fills the visual field. For a variety of examples that can be viewed full screen, see www.uniformillusion.com.

Here we present a series of novel visual illusions. This new class of illusions supports the idea that rich visual experience is reconstructed by the brain. The illusion appears when viewers are presented with a display that contains different but related central and peripheral stimuli (see Figure 1 for two examples; four additional examples of the uniformity illusion with different stimuli are presented in the appendix). The peripheral stimuli are perceived to assume the features of the central stimuli. This transition of perceptual content can take several seconds, giving rise to a shift in the perceived properties of the periphery. In Figure 1, the peripheral stimuli are the same in both images. Yet, when viewers keep their eyes focused on the centre for a few seconds, the peripheral stimuli take on the identity of the central stimuli, turning to hexagons in 1a, or circles in 1b. Several examples of such an illusory uniformity shift, including one with dynamic moving stimuli, can be viewed on www.uniformillusion.com.

It seems that almost anyone who views the displays will experience a uniformity illusion. In addition to the individual subjective experience, this article presents 8 experiments. These experiments had four goals. The first goal was to illustrate that the illusion consistently arises for a wide range of stimuli. Participants were asked to indicate the presence of a uniform display for shape, pattern, luminance, orientation, shade, identity and motion in displays in which the periphery differed from the centre (Experiments 1-7). To test whether participants were able to correctly identify changes, trials were included in which the display physically became uniform. The second goal was to quantify the basic properties of the illusion: how often it occurs and how long it takes to arise. To assess the baseline for speed and accuracy, Experiment 6 and 7 also included trials in which the centre and the periphery were identical from the start of the trial. The third goal was to explore one important parameter that appears to influence the illusion, namely the amount of (dis)similarity between the stimuli on the central patch and the periphery. The stimuli in Experiments 1-7 either had a small difference between the central patch and periphery, or a large difference, which allowed us to explore the effect of (dis)similarity on the occurrence and timing of the illusion. Finally, Experiment 8 addressed the question whether the subjective experience of the illusory uniformity shift was similar to the subjective experience of a physical uniformity shift. To this end, this experiment focused on metacognition.

Methods

Participants

20 participants, all naïve to the purpose of the experiments, took part in the experiments. Participants 1-12 (average age 28.5 years, 8 females) participated in Experiments 1, 4 and 5. Participants 1-11 (average age 27.3 years, 8 females) participated in Experiments 2 and 3. Participants 11-15 and 17-19 (average age 31.6 years, 4 females) participated in Experiment 6. Participants 11-20 (average age 34.2 years, 5 females) participated in Experiment 7 and participants 11-15 and 17-20 (average age 31.7 years, 5 females) participated in Experiment 8. All participants had normal, or corrected-to-normal vision. All experiments were approved by the ethical committee of the University of Sussex. Informed consent was obtained from all participants before participation. The number of participants per experiment varied from 8 to 12. Overall, the aim was to include around 10 participants in each version of the experiment (see Bonneh, Cooperman, & Sagi, 2001). Participation varied slightly per version since some participants were willing to participate for longer periods of time, completing more different versions of the experiment, while other participants completed only one, or a few versions.

General Procedure

In all experiments, participants were seated in a darkened room, with their chin on a chin-rest, at a distance of 63 cm from the 21.5 inch LED screen (height: 26.8 cm, width: 47.6 cm). They were instructed to, during trials, fixate on a central fixation spot, and to avoid blinking. During the experiment their eyes were tracked with an Eyelink eyetracker (EyeLink 2000, SR Research Ltd., Mississauga, Ontario, Canada). If participants moved their eyes away from the fixation spot (threshold for a saccade was set at 108°/second), or blinked, the trial was aborted, and replaced by a similar trial (with the same conditions as on the aborted trial) to ensure the same amount of trials per condition.

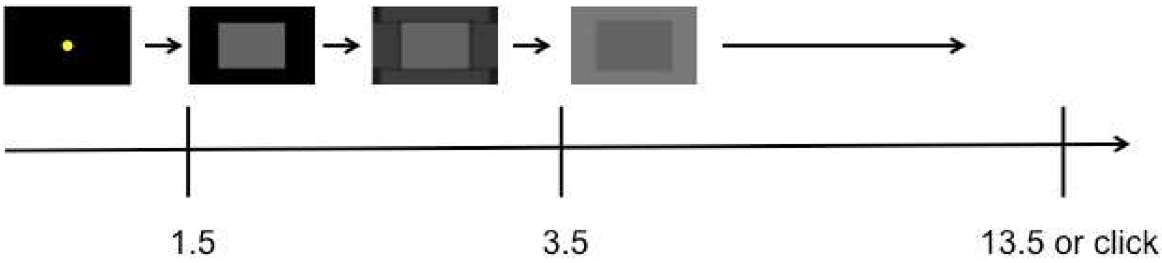


Fig 2:
Illustration of the sequence of events in a uniformity experiment. First the central patch was presented for 1.5 seconds, then the periphery faded in, then the entire display remained visible for 10 seconds, or until the subject clicked with the mouse (to indicate that (s)he thought the entire display was uniform).

Procedure Experiments 1-5

Each trial started with a fixation point, presented for 1.5 seconds. Then the central patch was presented, and the periphery faded in (which took approximately 2 seconds). After the periphery was completely faded in, the entire screen remained visible either for ten seconds, or until the participant responded, indicating perceptual uniformity (See Figure 2). Participants were instructed to click with the mouse as soon as the entire screen appeared in their experience to become uniform, but to not do anything when the central patch and the peripheral patch appeared different. For each experiment, the participant was explicitly instructed what the response/ no response conditions entailed (e.g. click only when the orientation of the line segments on the screen are all the same; do not click when there are line segments with deviating orientation). Each experiment had a different type of stimulus array, where the defining characteristic of the central stimulus, and thus the illusory percept depended on shape (Exp 1), orientation (Exp 2), luminance (Exp 3), shade (Exp 4) and motion (Exp 5). Figure 3 shows example displays for all 5 experiments.

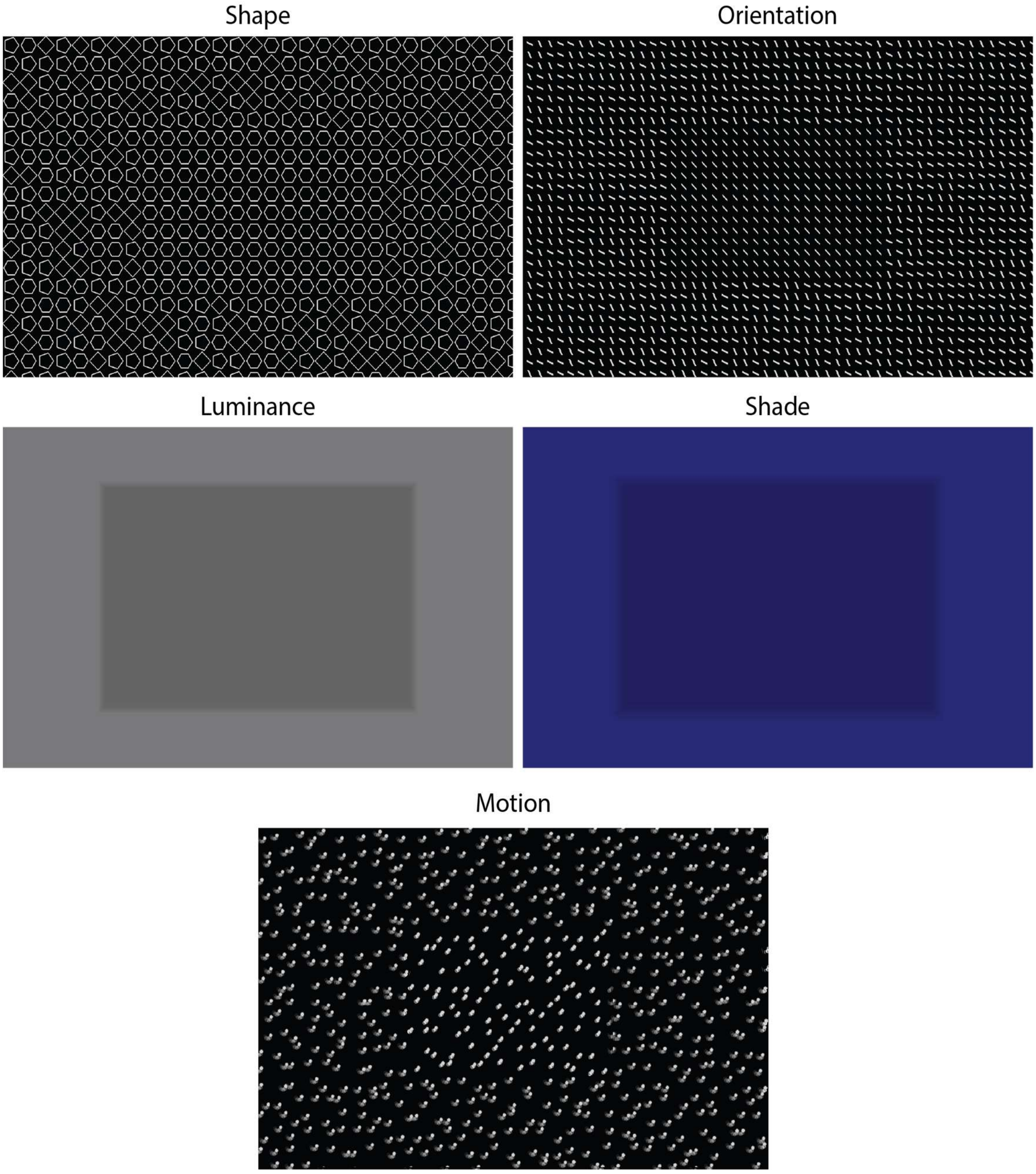


Fig 3:
Sample displays for the stimuli used in Experiments 1 - 5

In Experiments 1-5 there were two trial types: (i) *no change* trials in which the periphery remained dissimilar from the central patch for the duration of the trial, and (ii) *change* trials that mimicked the experience of the uniformity illusion, in which the periphery slowly changed from different to identical. This change would start at a randomly chosen moment between 2 and 3 seconds after fade in of the periphery was completed, and would take maximally 6 seconds.

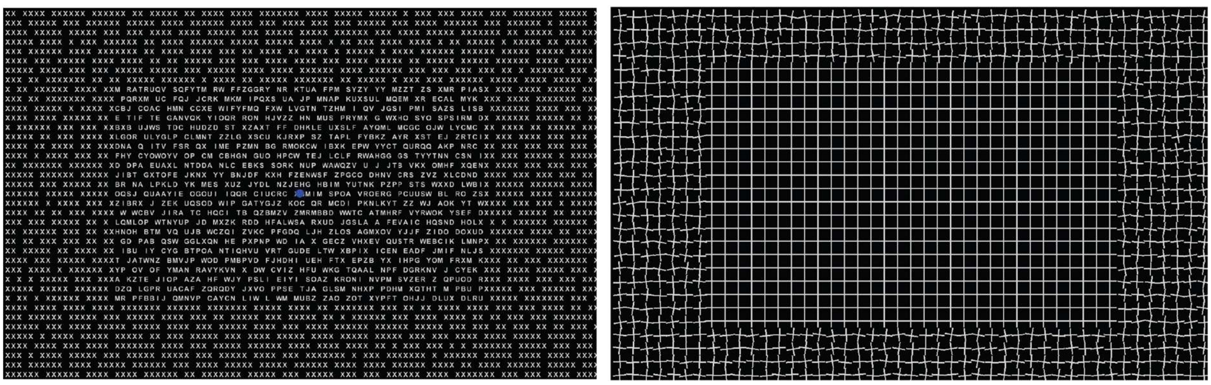
For both trial types, there were two levels of stimulus difference: a small difference or a large difference between central and peripheral patch. There were 20 small difference/no change trials, 20 large difference/no change trials, 10 small difference/ change trials and 10 large difference/ change trials. These 60 trials were presented in 3 blocks of 20 trials. The experiment lasted approximately 25 minutes.

<u>Procedure Experiments 6 and 7</u>

Experiments 6 and 7 (identity- and pattern-uniformity, see Figure 4) had the same 4 conditions as Experiments 1-5, plus an additional trial condition in which there was no difference between the central patch and the periphery from the start of the trial. These *no-difference* trials allowed us to quantify the ability to detect uniformity and the time it takes to respond to (physical) uniformity, to function as a baseline for the illusion conditions. The 5 conditions were randomly distributed throughout the experiment. In Experiments 6 and 7 participants saw 20 trials of each condition. The 100 trials (40 of which contained no real uniformity at any moment during the trial) were presented in 5 blocks of 20 trials, preceded by a 20 trial practice block (of which the trials were not included in the analysis). The experiments lasted approximately 50 minutes.

Fig 4:
Sample displays for the stimuli used in Experiments 6 and 7

Identity Pattern



Materials Experiment 1-7

The size of the central patch and the size of the stimuli differed per experiment. Furthermore, the luminance and hue of the stimuli and background also changed per experiment. In Table 1 these variables are specified per task.

Table 1
Stimulus characteristics of the different uniformity experiments. Distances and sizes are in degrees of visual angle (first width, then height), luminance is in candela per square meter, and hue is in CIE x,y coordinates. In the shape condition, peripheral stimuli had the same area size as the central stimulus. In the orientation condition the peripheral line segment had the same length as the central line, the size of the central line segment is given as width x length, distance denotes space between two centres of line segments. In the motion condition the size of the rotating dot is provided, and distance denotes the space between outer edges of the imaginary circle that the dot is rotating on.

	Size central patch	**Size stimulus**	**Distance between stimuli**	**Luminance stimulus**	**Hue stimulus**	**Luminance background**	**Hue background**
1. Shape	26.2 x 14	Radius: 1.1	0.36	42	0.287, 0.315	0	0.213, 0.204
2. Orientation	25.3 x 13.3	0.14 x 0.82	0.87	42	0.287, 0.315	0	0.213, 0.204
3. Luminance	27.9 x 15.3			8.9	0.281, 0.307	10.8 - 13	Different per condition
4. Shade	27.9 x 15.3			1	0.148, 0.072	1.2 – 1.7	0.148, 0.072
5. Motion	25.3 x 13.3	Radius: 0.14	0.14	42	0.287, 0.315	0	0.213, 0.204
6. Identity	25.3 x 13.3	0.43 x 0.52	0.1	42	0.287, 0.315	0	0.213, 0.204
7. Pattern	29.5 x 16.7	0.86 x 0.86	0	42	0.287, 0.315	0	0.213, 0.204

What was meant by small and large differences between the centre and the periphery also varied per task. The corresponding stimuli are specified in Table 2. In the Experiment 3 (luminance) and 4 (colour), the boundary between foreground and background plane was "soft", in the sense that there was a small area (with a width of approximately 0.3° in visual angle), on all sides of the central plane, between centre and periphery that linearly transitioned from foreground colour/luminance to background colour/luminance. For an example of the stimuli that were used see: www.uniformillusion.com.

In Experiments 1, 2, 6 and 7 (shape-, orientation-, identity- and pattern-uniformity) after fade in of the periphery, "blips" were presented every 250 milliseconds, for 6 seconds. A blip consisted of a blank screen being presented for 16 ms. On catch trials actual changes to peripheral stimuli would always coincide with a blip. Thus, on catch trials, the blips prevented participants from noticing slight movements in the periphery. For instance, when a line segment changes its orientation without blips, this leads to detectable motion. Consequently, if the stimuli were presented without blips, there would be a difference between *no change* trials (in which there is no perceivable motion of the stimuli) and the *change* trials (in which there would be perceivable motion of the stimuli). So, by introducing the blips, all trial types were equated with regards to perceivable motion.

Table 2
Description of the stimuli that constituted large and small differences in experiment 1-7.

	Central stimulus	**Small difference**	**Large difference**
1. Shape	Circles	Pentagons and Hectagons	Diamonds, pentagons and hectagons
2. Orientation	45 degrees tilted to the left	Line segments tilted 30 or 60 degrees	Line segments tilted 20 or 70 degrees
3. Luminance	Grey plane : 0.281, 0.307, lum: 8.9	Grey plane : 0.282, 0.308, lum: 10.8	Grey plane : 0.282, 0.309, lum: 13
4. Shade	Blue plane: 0.148, 0.072, lum: 1	Blue plane: 0.148, 0.072, lum: 1.2	Blue plane: 0.148, 0.072, lum: 1.7
5. Motion	Dots rotating on an imaginary circle (radius 0.43°) with a speed of 3.14 to 7.29 radians per second	Same dots, same circle radius, speed: x 3	Same dots, same circle radius, speed: x 5
6. Identity	Random letters picked from all letters from the alphabet	Letter/x morphs	Xs
7. Pattern	Cross as part of a regular pattern	Cross rotated by 1 to 4 degrees, displaced along both x- and y-axis by 1 to 4 pixels	Cross rotated by 1 to 10 degrees, displaced along both x- and y-axis by 1 to 10 pixels

<u>Procedure and Materials Experiment 8</u>

In this letter confidence task, the stimuli were identical as the ones used in Experiment 6, with Xs and Mixed letters (large difference category) and Letter/X morphs (small difference category). These stimuli were selected, because the previous experiment showed that the letter stimuli evoked the uniformity illusion consistently and within a short amount of time following peripheral fade in. The peripheral stimuli were either mixed letters, uniform Xs or letter/X morphs. The central patch was either empty, consisting of mixed letters or of uniform Xs (see Figure 5). All combinations between peripheral patch and central patch could occur, except with peripheral morphs the central patch could not be empty. This meant there were 8 conditions in total. There were 20 trials per condition, and all trials were randomly intermixed throughout the experiment. The resulting 160 trials were divided in 8 blocks of 20 trials.

As in the previous experiments, the trial started with a central fixation spot presented for 1.5 seconds. Then, the central patch was presented and the periphery faded in. In this case, after fade in, the stimuli remained visible for 6 seconds and then disappeared. Participants then indicated whether, at the end of the trial, the peripheral stimuli were mixed letters or uniform Xs, with a non-speeded forced choice. After this judgment the participant indicated how certain they were by choosing one of 4 boxes numbered 1 to 4, with 1 representing ‘total guess’, and 4 representing ‘very certain’.

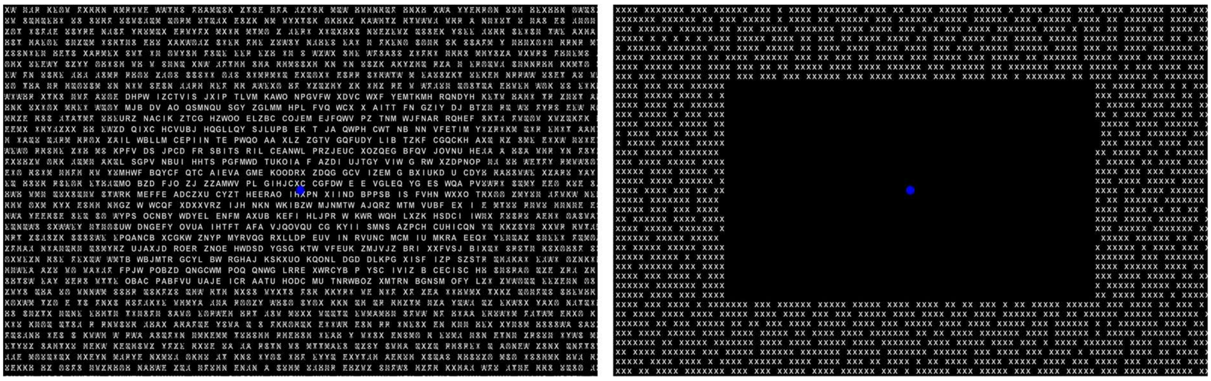


Fig 5:
The confidence experiment (Exp 8) was similar to the uniformity experiment, except now the display (after the periphery had faded in) remained visible for 6 seconds. After the display disappeared the subject indicated the identity of the stimuli in the periphery, and confidence in this judgment. The central patch could be filled with stimuli that were the same or different from the peripheral stimuli (see left), or it could remain empty (see right).

Analysis Experiment 1-7: Control

Experiment 1-7 included ‘change’ trials in which the periphery actually slowly changed to become identical to the central patch. These trials were included to test whether participants were able to accurately respond to physical shifts to uniformity. At the start of each trial, whether a change or no-change trial, a time point was selected to be the onset of a time-window in which the display was going to change from different to uniform. In change trials, this change was executed. In no-change trials, this change was not executed. For both change and no-change trials (excluding those trials in which participants responded prior to the onset of the change), we calculated the percentage of trials in which participants indicated that they had seen a uniformity shift. For no-change trials (in which the uniformity illusion could occur) participants indicated that they had seen a uniformity shift on 68% of the trials (ranging from 46% to 93% over the seven experiments). For change trials (in which an actual uniformity shift occurred) participants indicated that they had seen a uniformity shift on 89% of the trials (ranging from 71% to 96% over the seven experiments). Participants were significantly more likely to indicate that they had seen a uniformity shift on change trials than no change trials ($t_6 = 3.44$, $p = .01$), which a) shows that participants were paying attention to the displays and not just pushing the response button randomly and b) suggests that participants were able to accurately report their perceptual experiences.

Analysis Experiment 1-8: Illusion

In *no change* trials (when the periphery remained different from the central patch throughout the trial) a response was classified as indicating an illusory shift to uniformity when observers clicked the mouse at any point during the trial. On *change* trials (when the periphery gradually became identical to the centre starting 2-3 seconds after the fade in of the periphery) a response was classified as indicating an illusory shift to uniformity when observers clicked the mouse before the peripheral stimuli started changing (so within the 2-3 second time-window at the start of each change trial when these trials were still identical to the no change trial). All other responses were coded as ‘no illusory shift'. To calculate the occurrence of illusory shift, the number of trials in which participants indicated a uniformity shift was calculated relative to the total number of trials. For the reaction times, the time from complete fade in of the periphery until the mouse click indicating uniformity was calculated for each level of difference between the central and peripheral stimuli.

Results

Experiments 1-5: shape, orientation, luminance, shade & motion

For each experiment, participants were instructed to click the left mouse button when they saw that the display went from differing between centre and periphery to uniform. The percentage of illusory uniformity responses relative to the total amount of trials was calculated for each type of stimulus, for the two levels of difference between the central and peripheral stimuli. All 5 experiments show that the uniformity illusion consistently occurs (M= 83% of trials, varying from 74-91%), indicating that shape, orientation, luminance and motion are all susceptible to the uniformity illusion. The uniformity illusion does require participants to fixate on the central screen for at least 2 second before the uniformity shift occurs (M = 2.8 seconds, range 1.8-5.2 seconds over the 5 experiments). Figure 6 illustrates the results of each of 5 experiments, specifying both the rate of report for illusory uniformity shifts and time to illusion onset for displays in which the difference between the central patch and the periphery was large, and when that difference was small.

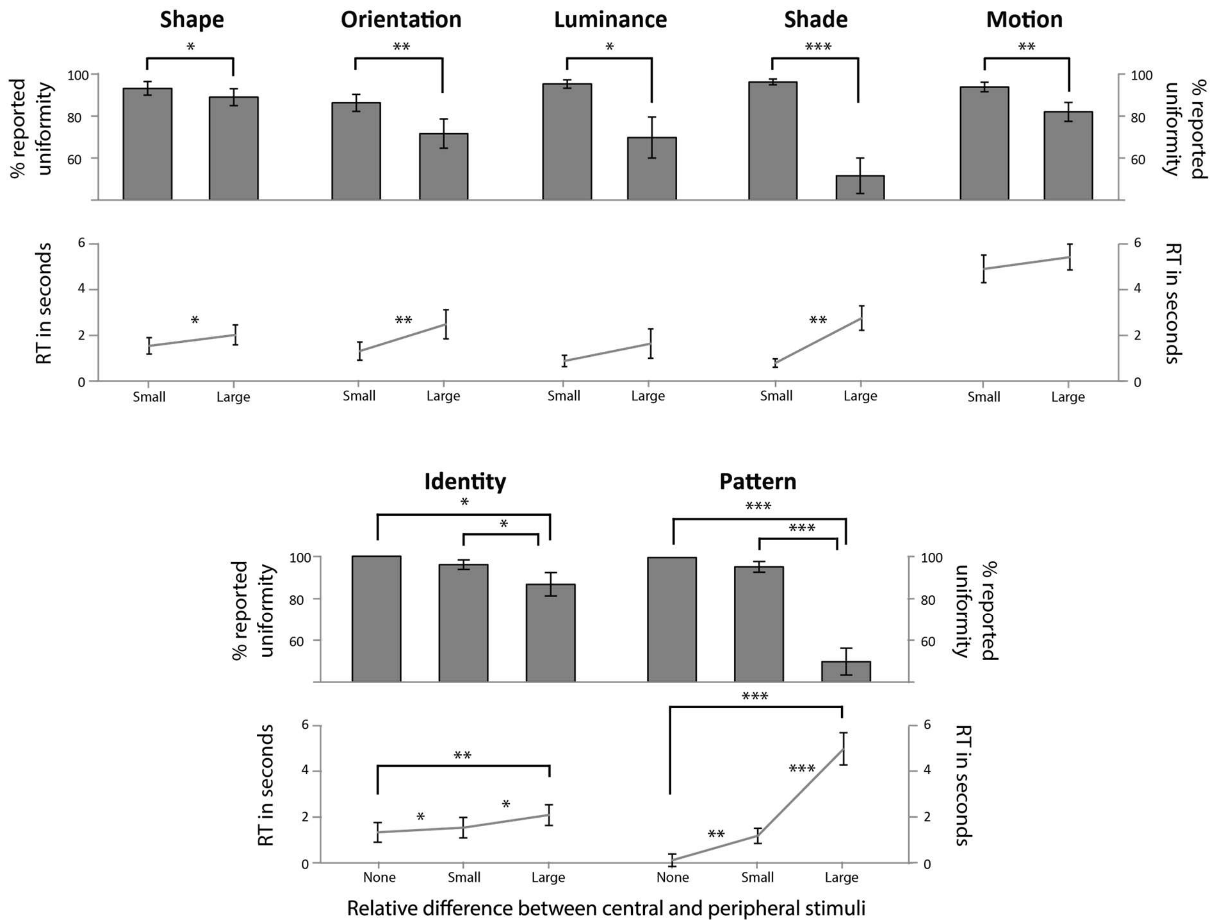


Fig 6:
An overview of seven experiments documenting the uniformity illusion. In each experiment, participants judged whether a display was uniform. For all tested stimuli, participants experienced illusory uniformity. The illusion occurred more often, and occurred faster, when the difference between central and peripheral stimuli was smaller. Significant differences are indicated by asterisks (* = p < .05, ** = p < .01, *** = p < .001).

When the difference between periphery and the central patch was larger, participants were less likely to see the uniformity illusion. Moreover, in those cases where the difference between stimuli in the centre patch and the periphery was larger, the uniformity illusion was also slower to develop, although this difference did not reach significance in Experiments 3 (luminance) and 5 (motion). The relevant results are summarized in Table 3.

Table 3

Results for experiments 1-5. For each experiment, the percentage of reported uniformity (which reflects the percentage of illusory uniformity shifts), and the average reaction time (reflecting the time between the fade in of the periphery and the button press indicating uniformity) are reported for each type of trial.

	Exp 1: Shape		Exp 2: Orientation		Exp 3: Luminance		Exp 4: Shade		Exp 5: Motion	
% Reported Uniformity	Means		Means		Means		Means		Means	
	Small diff	Large diff	Small diff	Large diff	Small diff	Large diff	Small diff	Large diff	Small diff	Large diff
	93.1	88.9	86.2	71.6	95.2	69.7	96.1	51.2	93.8	81.9
	Statistics		Statistics		Statistics		Statistics		Statistics	
	$t_{11} = 2.32$ $p = .04$ $d = 1.4$		$t_{10} = 3.56$ $p = .005$ $d = 2.25$		$t_{10} = 2.96$ $p = .014$ $d = 1.87$		$t_{11} = 5.66$ $p < .001$ $d = 3.41$		$t_{11} = 3.28$ $p = .007$ $d = 1.98$	
	Means		Means		Means		Means		Means	
Reaction times	Small diff	Large diff	Small diff	Small diff	Large diff	Large diff	Small diff	Large diff	Small diff	Large diff
	1.56,	2.04	1.31	2.48	1.14	2.48	0.95	5.39	4.93	5.45
	Statistics		Statistics		Statistics		Statistics		Statistics	
	$t_{11} = 2.94$ $p = .013$ $d = 1.78$		$t_{10} = 4.15$ $p = .002$ $d = 2.62$		$t_{10} = 1.51$ $p = .16$ $d = 0.95$		$t_{11} = 3.84$ $p = .003$ $d = 2.31$		$t_{11} = 1.43$ $p = .18$ $d = 0.86$	

Experiments 6-7: Identity & Pattern

As in Experiments 1-5, participants saw stimuli in which the central patch was slightly different from the surrounding periphery, or very different from the surrounding periphery. In addition to this, participants also viewed stimuli in which the central patch was not different from the periphery. In the *no-difference* trials, the periphery and central patch were identical from the fade in of the periphery, and these trials can therefore functions as a baseline to indicate how accurately participants can detect uniformity, and how long it takes for participants to report uniformity when uniformity is present. As to be expected, participants were highly accurate in detecting that the central patch was identical to the periphery, and relatively fast to respond. The other two types of trials, in which the periphery differed from the central patch, showed a strong potential to evoke uniformity illusions. Experiments 5-6 show that the uniformity illusion occurs when the centre differs from the periphery in the identity of the stimuli (Xs compared to other letters) and when the pattern in which stimuli are presented is different between the central patch and the periphery (a so-called healing grid). The uniformity occurs about 1.8 seconds after display onset for the identity uniformity and 3.2 seconds for the healing grid on average. When compared to the baseline condition (no-difference trials) this shows that the time the uniformity illusions takes to develop can vary quite dramatically over stimuli, as the identity uniformity illusion occurs almost immediately, while the pattern uniformity illusion takes more time to develop.

As in Experiment 1-5 participants were less likely to see the uniformity illusion when the difference between periphery and the central patch was larger. Likewise, in those cases where the difference between stimuli in the centre patch and the periphery was larger, the uniformity illusion was also slower to develop. For the relevant ANOVAs and follow up t-tests for Experiments 6 and 7, see table 4.

Table 4

Overview of the results of Experiments 6 and 7. For each experiment, there are two rows of results, the first one reflecting the percentage of reported uniformity (which reflects the percentage of illusory uniformity shifts for the small and large difference trials), the second row reflecting the average reaction time for each type of trial, reflecting the time between the fade in of the periphery and the button press indicating uniformity.

Exp 6: Identity							
	Means			*One way ANOVA*	*Follow –up t-tests*		
	No diff	Small diff	Large diff		Small vs No Difference	Small vs Large Difference	Large vs No Difference
% Reported Uniformity	100	94.7	82.2	$F_{2,14}$=5.8 p=.014 η^2 = .46	t_7 = 1.79 p = .12 d = 1.35	t_7 = 2.66 p = .033 d = 2.01	t_7 = 2.4 p = .047 d = 1.82
Reaction Times	1.35	1.56	2.11	$F_{2,14}$=8.5 p = .004 η^2 = .55	t_7 = 3.42 p = .011 d = 2.58	t_7 = 3.4 p = .011 d = 2.57	t_7 = 4.1 p = .005 d = 3.09
Exp 7: Patterns							

	Means			*One way ANOVA*	*Follow –up t-tests*		
	No diff	Small diff	Large diff		Small vs No Difference	Small vs Large Difference	Large vs No Difference
% Reported Uniformity	100	94	33	$F_{2,18} = 55.4$ $p < .001$ $\eta^2 = .86$	$t_9 = 1.73$ $p = .12$ $d = 1.16$	$t_9 = 7.71$ $p < .001$ $d = 5.14$	$t_9 = 9.35$ $p < .001$ $d = 6.23$
Reaction Times	0.23	1.3	5.11	$F_{2,18} = 63.2$ $p < .001$ $\eta^2 = .88$	$t_9 = 3.95$ $p = .003$ $d = 2.64$	$t_9 = 7.66$ $p < .001$ $d = 5.11$	$t_9 = 7.15$ $p < .001$ $d = 4.77$

Experiment 8

In this final experiment we investigated how perceptual judgment of the peripheral stimulus varied as a function of the central stimulus, and how confident participants were of their perceptual judgments. Experiments 1-7 suggest that the observers see a change in the periphery, while the physical display remains the same. However, this still leaves the possibility of a response bias: perhaps the observers do not actually see a change, but simply report seeing a change. Experiment 8 was designed to address this issue, by measuring metacognition. Participants indicated the specific nature of the stimuli they saw in the periphery at the end of each trial. This change in the design allowed us to explore whether people had an illusory experience (when they reported the stimuli from the central patch for the periphery, while the true peripheral stimuli were different) and test their subjective confidence in that judgment for illusory as well as real perception. The responses and confidence judgements of the participants are summarized in Table 5 and Figure 7.

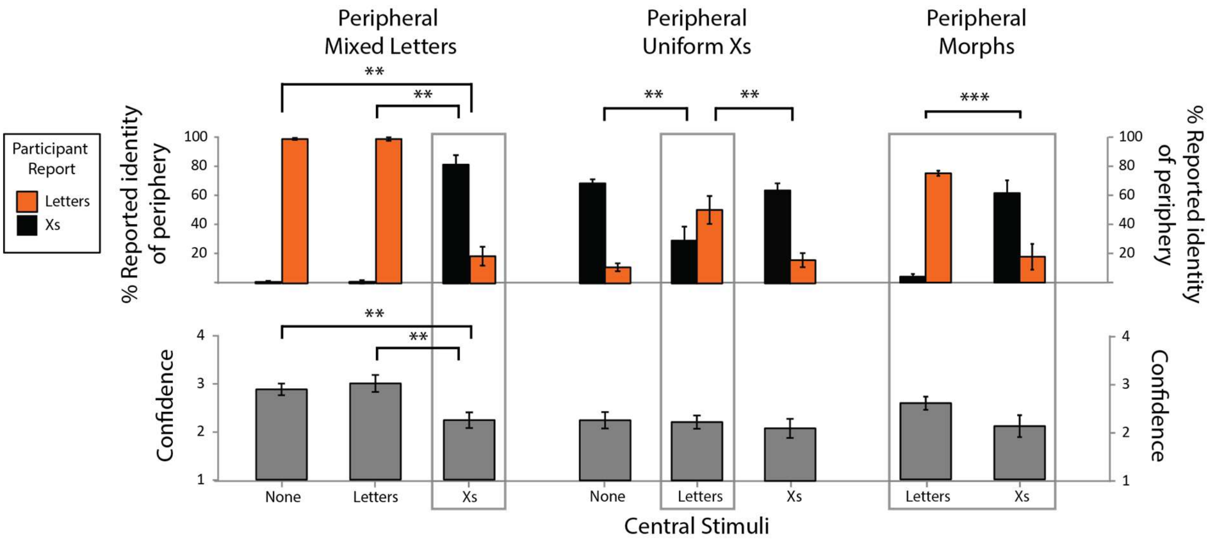


Fig 7: An overview of the results of Experiment 8. The top panels indicate how often subjects saw mixed letters (orange bars) or uniform Xs (black bars). The bottom panel shows average confidence ratings (1 = guess, 4 = certainty). When central stimuli differed from the periphery illusory uniformity shifts occurred, as indicated by the grey boxes. Participants were highly confident about these illusory judgments (bottom panel). Significant differences are indicated by asterisks (** = p < .01, *** = p < .001).

The identity of the central patch changed the perception of the periphery when the periphery consisted of mixed letters ($F_{2,16} = 151.4$, MSE = 0.014, $p < .001$, $\eta^2 = .95$), when the periphery consisted of uniform Xs ($F_{2,16} = 12.4$, MSE = 0.053, $p = .001$, $\eta^2 = .61$) and when the periphery consisted of morphs ($t_8 = 6.45$, $p < .001$, $d = 4.3$). When the periphery consisted of uniform Xs, presenting mixed letters centrally increased the percentage of letter-reports for the periphery compared to when the periphery was empty ($t_8 = 4.49$, $p = .002$, $d = 2.99$) or filled with Xs ($t_8 = 2.92$, $p = .017$, $d = 1.95$). When the periphery consisted of mixed letters, presenting uniform Xs in the centre increased the percentage of X-reports for the periphery compared to when the periphery was empty ($t_8 = 11.52$, $p < .001$, $d = 7.68$) or filled with mixed letters ($t_8 = 10.51$, $p < .001$, $d = 7$).

Table 5 Overview of the results of Experiment 8. The first row of results shows the percentage of trials on which participants reported seeing letters. The second row of results shows the average confidence rating (range 1-4) for each type of trial.

Experiment 8: perceptual judgments								
	Peripheral mixed letters			Peripheral uniform Xs			Peripheral morphs	
Central stimuli	empty	letters	Xs	empty	letters	Xs	letters	Xs
% reported letters	99	98.9	18.6	13.9	63.2	20	94.7	22.5
Confidence	3.34	3.5	2.55	2.56	2.52	2.37	2.98	2.38

Table 5 shows that confidence was not extremely high, but still above the average of 2 in all conditions, and overall seemed relatively similar for judgements of real and illusory displays. When the peripheral stimuli were mixed letters, the presence of a uniformity illusion (i.e. seeing uniform Xs in the periphery) was accompanied by a slight decrease in confidence in that report ($F_{2,16}$ = 15.1, MSE = 0.14, p < .001, η^2 = .65). However, when the peripheral stimuli were uniform Xs, confidence was equally high when these stimuli were misperceived as mixed letters, as when they were correctly perceived as uniform Xs ($F_{2,16}$ = 1.46, MSE = 0.195, p = .26, η^2 = .15).

Discussion

Experiments 1–7 show that central stimuli can reliably create illusory uniformity of stimuli into the periphery for shape, orientation, luminance, shade, motion, identity and pattern. Observers reported the uniformity illusion in 33 to 96% of displays, depending on type of stimulus, and degree of difference between the central patch and the periphery. These results illustrate a novel visual illusion in which the perceived pattern of the peripheral vision is uniformly changed to that of central vision. Somewhat similar phenomena have been reported previously (Mackay, 1964, The Healing Grid Illusion by Kanai presented in Annual Visual Illusion Contest). However, the previous reports were anecdotal, and our present set of experiments is the first to systematically study this phenomenon with a wide range of visual attributes. Experiment 8 shows that observers rated their perception of illusory uniform stimuli as equally reliable to physically uniform stimuli. However, there was a subtle difference in confidence ratings for peripheral mixed letters, which suggests that illusory uniformity might be somewhat different from the experience of physical uniformity. Overall, this series of experiments illustrate the strength and versatility of the uniformity illusion.

The uniformity illusion builds up gradually: All experiments indicate that the illusion occurs only after keeping fixation on the central patch for some time. The exact time varied per stimulus type, with the motion uniformity illusion taking longest to develop. Moreover, all experiments showed that when central and peripheral stimuli are more dissimilar, participants less often reported seeing uniformity, and if they did, time to onset of the illusion increased. This delay suggests that adaptation to peripheral signals may play an important role in the reduction of visibility of the original peripheral stimuli (Ditchburn & Ginsborg, 1952). Future research should explore the exact role of adaptation within the visual system to determine the exact role it plays within the uniformity illusion.

Another key feature of the uniformity illusion is that visual information visual information in the periphery does not disappear when the observer adapts to it. Instead the observer now perceives the central stimuli to be present in the periphery as well. In this regard, the illusion bears similarity to the phenomenon of perceptual misbinding described by Wu and colleagues (Wu, Kanai, & Shimojo, 2004), where dots in the periphery are perceived to have the same combination of features (colour and direction of movement) as the stimuli that are perceived in the centre of the visual field. However, one important difference between this illusion and the uniformity illusion is that the perceptual misbinding illusion occurs immediately, and does not require adaption (Kanai, Wu, Verstraten, & Shimojo, 2006). Other illusions in which visual information is added to the subjective percept such as the filling-in of the blind spot, the watercolor illusion (Pinna, Brelstaff, & Spillmann, 2001), neon colour spreading (Grossberg & Mingolla, 1985), visual phantoms (Kitaoka, Gyoba, & Sakurai, 2006; Sakurai & Gyoba, 1985; Tynan & Sekuler, 1975), lightness illusions (Kitaoka et al., 2006; Zavagno & Caputo, 2001), and filling-in amodaly completed Kanisza figures (Kanizsa, 1976), also occur without preceding adaptation.

Taking into account the relatively large amount of time before the uniformity illusion occurs, it seems most related to Troxler fading in which small 'empty' patches, or objects (such as yellow circles) are filled in with the static (Balas & Sinha, 2007; Ramachandran & Gregory, 1991) or moving background texture (Bonneh et al., 2001; Ramachandran & Anstis, 1990) after fixating a central viewing point for an extended period of time. However, in contrast to the relatively local nature of perceptual filling-in, the uniformity illusion affects large parts of the visual field involving long angular distances.

The uniformity illusion occurs for a wide range of stimulus-types. This suggests that the uniformity illusion is guided by a general mechanism of visual processing. One possibility is that the illusion is rooted in the principle that the brain implements a 'hierarchical prediction machine' (Clark, 2013). In this view, the following cascade of events may underlie PO: 1) Initially, the incoming visual information of the centre and periphery of the display is strong enough to generate an accurate percept of the entire visual display; 2) As the observer maintains fixation on the centre of the display, sensory input from the periphery deteriorates more than information from the centre of the display (Schieting & Spillmann, 1987; Smith, Singh, Williams, & Greenlee, 2001); 3) In the on-going cycle of adjusting predictions relative to sensory prediction errors, the peripheral visual input loses its informative strength (Riggs, Ratliff, Cornsweet, & Cornsweet, 1953); 4) The prediction for the identity of the elements in the visual field is dominated by the more reliable information from the centre of the visual field, possibly combined with a default prior of surface uniformity. With the peripheral visual input too weak to update the current predictions, this process causes the properties of the central stimuli to be projected across the periphery.

It remains to be seen whether the perceptual "filling-in" of the periphery with the stimuli presented in the central patch (as described above in step 4) truly represents an active perceptual process in which the central stimuli are 'projected' onto the periphery. This question reflects an ongoing discussion about the nature of filling-in illusions in general (Dennett, 1992; Pessoa, Thompson, & Noë, 1998): are the illusory parts of the visual scene actively generated ('filled in'), or are these illusory patches the result of a more passive process in which the periphery only appears to be filled in with information that receives more attention. Experiments focussing on the neural activation underlying other filling-in illusions, such as neon color spreading, have shown evidence for active filling-in at the earliest stages of perception (Chong, Familiar, & Shim, 2016; Hsieh & Tse, 2009; Komatsu, 2006; van de Ven, Jans, Goebel, & De Weerd, 2012). However, the current experiments do not provide direct evidence for active filling-in of the periphery. It is possible that the subjective experience of uniformity is instead due to attenuation of information that distinguishes the differences between the central patch and the periphery, which causes observers to perceive the whole visual field as uniform. A study of so-called 'perceptual metamerism' by Freeman and Simoncelli (2011) indeed shows when viewing natural images, subjects can fail to detect substantial distortions to the periphery (while preserving low-level image properties). At the present time, therefore, it is impossible to decide whether the uniformity illusion is based on active filling-in, or passive assumptions about the nature of a visual stimulus. We have observed, however, that when the central patch in a display evoking the uniformity illusion suddenly changes (for example, the central stimuli are lines tilting to the left within a periphery of mixed orientation lines, and after 60 seconds the central lines become right tilting), the illusory periphery seems to persists for a while before the periphery changes to the identity of the central patch. It thus seems the illusion is not immediately halted or overwritten when observers see new central information. This persistence of the illusory periphery, which can be viewed at uniformillusion.com/p/luminance-illusion-change.html, suggests a relative active form of filling-in. More supporting (neural) evidence should be gathered, however, before we can draw any strong conclusion about the processes underlying the uniformity illusion.

Uniformity illusions appear for stimuli with very different characteristics, ranging from a display filled with objects moving at different speeds to a uniformly grey display with a difference in luminance. We have created further examples for colour, blurriness, density and size (see Appendix). Much like binocular rivalry (Tong, Nakayama, Vaughan, & Kanwisher, 1998), the uniformity illusion can directly manipulate of the content of visual perception, and has been the basis of many studies exploring consciousness. The extremely wide range of features for which uniformity illusions occur, combined with its global effects on the percept, provides exciting additional potential to study how the brain constructs (visual) conscious experiences.

In summary, this novel visual illusion suggests that conscious visual experience reflects active reconstruction in which precise foveal information is seen to replace imprecise peripheral information. This may explain why our conscious experience appears to be rich and detailed across the entire visual field, despite the impoverished informational contents in peripheral vision.

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MO with input from co-authors. YP designed the displays, programmed the experiments and collected the data. All authors approve the manuscript.

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Appendix

Four additional examples of the uniformity illusion with blurriness, colour, density and size as examples (starting from the top left and moving clockwise). The periphery is either blurrier, greener, less dense, or consists of larger circles than the centre. However, if you fixate the centre of the image for a prolonged period of time, the periphery seems to take on the properties of the centre.